

Technical aspects in dark matter investigations

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Abstract.

Some theoretical and experimental aspects regarding the direct dark matter field are mentioned. In particular some arguments, which play a relevant role in the evaluation of model dependent interpretations of experimental results and in comparisons, are shortly addressed.

Many Dark Matter (DM) candidate particles have been proposed in theories extending Particle Physics beyond the Standard Model (SM). A large number of possibilities is available in different scenarios, and model frameworks, for particles with very different phenomenology and interaction type with ordinary matter. A wide literature is available.

From the experimental point of view, many detection processes can be considered in order to study the DM particle interaction with the target materials. One of the many cases is the elastic scattering on target nuclei where the measured quantity is the nuclear recoil energy. However many DM candidates can give rise to signals that either have totally an electromagnetic nature (see e.g. [1]) or involve electromagnetic signals associated to nuclear recoils (see e.g. [2, 3]); obviously, approaches that are based on multiple subtraction procedure of the electromagnetic component of the experimental counting rate are blind to these latter scenarios. It is worth noting that also the neutralino in supersymmetric extensions of the SM could have, in some cases, interaction producing e.m. radiation rather than nuclear recoil. Moreover, well known side processes for nuclear recoils exist (such as recoils induced by neutrons, fission fragments, end-range alphas, surface electrons, etc.).

In order to interpret the experimental result of a direct search experiment many theoretical and experimental parameters and models appear in the evaluation and many hypotheses must also be assumed. Large possibilities are open considering the lack of knowledge about the real nature of the candidate, its distribution in the Galaxy, its coupling to target materials, etc. In addition, as regards calculations, one has to consider that: i) each model requires its parameters; ii) each parameter has an allowed range of values and not just a single value; iii) uncertainties in the models and in the parameters can play a relevant role in model dependent interpretations of results and in comparisons.

In the following just few of these quantities, models and parameters – mostly for the case of DM interactions on nuclei – are reminded as examples:

- cross section, mass, and other quantities describing the phenomenology and the space parameter of the considered DM candidate particle;
- Spin-Independent (SI) and/or Spin-Dependent (SD) interaction: elastic scatterings with electromagnetic contribution arising from excitation of bound electrons, inelastic scatterings on target nuclei with either SI and/or SD coupling in various scenarios, interaction of light DM either on electrons or on nuclei with production of a lighter particle, preferred interaction with electrons, conversion of DM particles into e.m. radiation, etc.;
- Effective couplings to nucleon: possible isospin dependence of the couplings can be considered; effective DM particle-nucleon coupling strengths for either SI and/or SD interaction can be defined, and this is important in the comparison of results obtained with experiments using different target nuclei depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with ^{23}Na and ^{127}I).
- Form Factor: it depends on the target nucleus; there is not a universal formulation for it, many profiles are available in literature; in these profiles some parameters – whose value is not fixed – appear. In case of SD interaction there is no decoupling between nuclear and DM particles degrees of freedom and it depends on adopted nuclear potential; the form factor profiles can differ one by another by order of magnitude; the value strongly affects the expected signal and the model dependent interpretation of the results;
- Spin Factor: in the SD interaction it is a crucial quantity. It depends on the nuclear potential; large differences in the measured counting rate can be expected when you consider different target nuclei, different modelizations and when they have different unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with ^{23}Na and ^{127}I);
- Scaling Law: the experimental observable in direct detection when searching for scatterings of DM particles on target nuclei is the nucleus cross section of the interaction; in order to compare the results obtained by using different target nuclei a scaling law for cross section is required. For example, it has been proposed that two-nucleon currents from pion exchange in the nucleus can give different contribution for nuclei with different atomic number [4]; as a consequence the cross section for some nuclei can be enhanced with respect to others in the SI interactions even within the framework of the MSSM [4]; also this argument has a great relevance in the comparisons;
- Halo model and DM velocity distribution: the Dark Halo of the Galaxy is an open problem of the field; the expected counting rate for the DM signal depends on the local DM density and on its velocity distribution at Earth's position. The experimental observations regarding the dark halo of our Galaxy do not allow us to get information on them without introducing models. The uncertainties existing in these models, and in their parameters affect the expected counting rate and they must be taken into account. The effect of these uncertainties is very important considering also that each experiment generally use different target material, energy threshold, quenching factor, form factor, etc.. and also the fact that the expectation for different DM candidate particle is more sensitive to some of these parameters rather than others. In addition, as regard the velocity distribution, the possible existence of non-thermalized component of DM particles in the halo, due e.g. to the tidal stream of satellite galaxies of Milky Way, can give relevant contribution and impact in results and comparisons.

For some of the many other complementary aspects regarding uncertainties in the experimental results and in the comparison see e.g. ref. [5].

The DM direct experiments can be classified in two classes: experiments investigating a peculiar model independent DM signature able to point out the presence of a DM contribution in their measured rate, and experiments based on the comparison of their rate or of their recoil-

like candidates surviving many subtractions with an expectation calculated in one assumed scenario (which implies to adopt many assumptions and approximations).

As regard the first class of experiments, at present the only feasible model independent signature is the DM annual modulation exploited by the DAMA experiments at the Gran Sasso National Laboratory [6, 7, 8]. This experiment with the present DAMA/LIBRA and the former DAMA/NaI (exposed masses: $\simeq 250$ kg and $\simeq 100$ kg of highly radiopure NaI(Tl), respectively) set-ups has released so far a total exposure of $1.17 \text{ ton} \times \text{yr}$ over 13 annual cycles, obtaining a positive model independent evidence for the presence of DM particles in the galactic halo at 8.9σ C.L.. No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) has been found or suggested [6, 9, 7, 8, 10]. In the last years CoGeNT experiment with a P-type Point Contact Germanium detector reported a preliminary positive hint [11].

As regard the second class, these experiments, in order to reduce their experimental counting rate, generally perform huge data selections and many subtraction procedures; after all, they derive a set of recoil-like candidates. It is worth noting that not only uncertainties in the many applied large selection/subtraction procedures and in the related efficiencies are present, but well known side reactions exist giving recoil-like candidates surviving all the applied subtractions.

The use of different techniques and experimental approaches, different target materials and experimental conditions must be considered in the comparisons. Some general requirements for DM experiments must be satisfied. In particular, it is mandatory for an experiment to accurately know the energy scale and energy resolution in the keV energy range of interest; this is crucial especially for dis-uniform detectors (as the liquid noble gas ones; see their and other literature). In addition, it is mandatory to know the response of the detector at threshold validated by careful calibrations performed in the same condition as in the production runs. In some experiments, as e.g. DAMA/LIBRA, the energy scale and resolution are continuously measured by external/internal known sources from MeV down to the energy threshold [9] while in other experiments these quantities, in the low energy region of interest for DM investigation, are extrapolated from calibrations at much higher energy (see e.g. [12]).

Another important quantity – in the case of elastic scattering on target nuclei – in results and comparisons is the quenching factor, q_f and, in particular for double phase experiments, the L_{Eff} parameter, and their behavior at low energy. As regard L_{Eff} , tensions exist in the available measurements and also in theoretical estimation (see e.g. [13]). The sensitivity for DM particle of double phase experiments strongly depends on this quantity and a cautious approach in its extrapolation is mandatory in order to not overestimate experimental sensitivity. The quenching factor is a specific property of the employed detector(s) and not a general quantity universal for a given material. For example, in liquid noble-gas detectors, it depends, among other things, on the level of trace contaminants which can vary in time and from one liquefaction process to another, on the cryogenic microscopic conditions, etc.. In bolometers the quenching factor depends for instance on specific properties, trace contaminants, cryogenic conditions, etc. of each specific detector, while generally it is assumed exactly equal to unity. In scintillators, the quenching factor depends, for example, on the dopant concentration, on the growing method/ procedures, on residual trace contaminants, etc., and is expected to have some energy dependence. The uncertainty of q_f value is not easy to be deeply evaluated in neutron measurement and it can be large. In the last years it has been proposed a general empirical formula to derive the quenching factor values for each used detector [14]. For example it derives quenching factors values for NaI(Tl) larger at low energy than those usually adopted; in addition, the possible effect of channeling has also to be considered [3]. These two effects can play an important role in the interpretation of results and in comparisons.

As regard problems related to the application of multiple subtraction procedures of the measured counting rate, as pursued by experiments trying to identify the presence of recoil-

like events, some cases will be mentioned.

In particular, for the rate claimed by XENON-100 in an inner "fiducial" volume some arguments can be pointed out: i) the energy calibration of the underground detector has been carried out in significantly higher energy region than the claimed keV one, and thus the energy threshold, the energy scale, the energy resolution and all the necessary efficiencies for the many applied subtraction procedures are unproved; ii) the small number of available photoelectrons/keV in the underground detector, the huge detector disuniformity, the far UV scintillation light emission, etc. do not support that energy threshold; iii) the stability levels of all the cuts windows applied in the many subtraction procedures and of the related efficiencies have not been suitably proved; iv) the reproducibility of identical detector performances in different Xe liquefaction processes in the relatively large underground volume (as well as along production runs) and the needed level of stability of all the detector features during each data taking period have not been suitably proved as well; etc. Some other general aspects have been addressed in [12, 5, 13].

As regards recent results by CDMS-II [15], a huge selection of the available detectors and data is performed and many subtraction procedures are applied as well, further reducing to marginal the already very limited available exposure; the stabilities of all the applied cuts windows are unproved, the quenching factor is always assumed equal to unity, all the efficiencies values and their stability are not suitably proved as well, etc.

Finally it is worth noting that the limits achieved by experiments searching for DM particle giving rise to nuclear recoils, are not robust reference points. In fact as discussed before similar results are quite uncertain not only because of possible underestimated or unknown systematics in the huge data subtractions and in some experimental aspects, but also because the results refer only to a certain (generally largely arbitrary) set of assumptions. When one consider, for example, the energy threshold dependence of the exclusion plots, up to several orders of magnitude differences can be present between claimed and realistic evaluation of the experimental sensitivity.

In conclusion, all the arguments mentioned above allow one to understand that the uncertainties existing in the models and in their parameters, the sometimes not suitably determined experimental quantities, etc., can drastically affect model dependent results and comparisons. Thus the comparison of the results achieved by different experiments must be handled with very cautious attitude without neglecting the many sources of uncertainties. This holds in particular for model dependent exclusion plot, that cannot be considered as universal limit. Model independent approaches are mandatory.

References

- [1] R. Bernabei et al., *Int. J. Mod. Phys. A* 21 (2006) 1445; R. Bernabei et al., *Phys. Rev. D* 77 (2008) 023506; R. Bernabei et al., *Mod. Phys. Lett. A* 23 (2008) 2125.
- [2] R. Bernabei et al., *Int. J. Mod. Phys. A* 22 (2007) 3155.
- [3] R. Bernabei et al., *Eur. Phys. J. C* 53 (2008) 205.
- [4] G. Prezeau et al., *Phys. Rev. Lett.* 91 (2003) 231301.
- [5] R. Bernabei et al., *J. Phys.: Conf. Ser.* 203 (2010) 012040 (arXiv:0912.4200);
- [6] R. Bernabei et al., *La Rivista del Nuovo Cimento* 26 n.1, 1 (2003).
- [7] R. Bernabei et al., *Eur. Phys. J. C* 56, 333 (2008).
- [8] R. Bernabei et al., *Eur. Phys. J. C* 67, 39 (2010).
- [9] R. Bernabei et al., *Nucl. Instr. & Meth. A* 592 (2008) 297.
- [10] R. Bernabei et al., arXiv:0912.0660; *Can. J. Phys.* 89 (2011) 11; S.I.F. Atti Conf.103(2011) (arXiv:1007.0595); pre-print ROM2F/2011/12, TIPP2011 Conf., Chicago, USA (2011).
- [11] C.E. Aalseth et al., *Phys. Rev. Lett.* 106 (2011) 131301; *Phys. Rev. Lett.* 107 (2011) 141301.
- [12] R. Bernabei et al., ISBN 978-88-95688-12-1, pages 1-53 (2009) Exorma ed. (arXiv:0806.0011[astro-ph]).
- [13] J.I. Collar and D.N. McKinsey, arXiv:1005.0838; arXiv:1005.3723; J.I. Collar, arXiv:1006.2031; arXiv:1010.5187; arXiv:1103.3481; arXiv:1106.0653; arXiv:1106.3559.
- [14] V.I. Tretyak, *Astrop. Phys.* 33 (2010) 40
- [15] CDMS-II Coll., in this Proc. and references therein.